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The effect of planetary-scale divergent circulation on the interannual variation of the summertime stationary eddies: the tropical easterly jet

By TSING-CHANG CHEN and MING-CHEN YEN, *Atmospheric Science Program, Department of Geological and Atmospheric Sciences, Iowa State University, 3010 Agronomy Building, Ames, IA 50011, USA*

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ABSTRACT

The tropical easterly jet is primarily composed of summertime stationary eddies over the monsoon region. Thus, the interannual variation of the former follows the interannual variation of the latter. Analyzing the 200-mb wind fields generated by the Global Data Assimilation System of the National Meteorological Center for the past decade, we found that the weakening (or strengthening) tropical easterly jet and stationary eddies are coincident with the weakening (or strengthening) of planetary-scale divergent circulation. The streamfunction budget analysis was performed to infer the possible link between interannual variations of stationary eddies and divergent circulation. A simple barotropic model with the forcing derived from the divergence of the vorticity flux of long-term climatology and summers of the weak and strong tropical easterly jet was used to simulate summer-time stationary eddies. The numerical results demonstrate the argument that the weakening (or strengthening) and of the tropical easterly jet of summer-time stationary eddies over the monsoon region is caused by the weakening (or strengthening) of the planetary-scale divergent circulation, which may be attributed to the interannual variation of tropical diabatic heating.

1. Introduction

As delineated by Krishnamurti (1971), the tropical easterly jet is a major feature of the upper tropical circulation during the northern summer. It was revealed by previous studies that this jet varies in its strength and position from year to year. Kobayashi (1974) observed that the strength of the tropical easterly jet correlates positively with the Indian monsoon rainfall; the strong (weak) tropical easterly jet is associated with positive (negative) rainfall anomalies. Contrasting the tropical circulation during the 1967 (normal rainfall) and 1972 (drought) summers, Kanamitsu and Krishnamurti (1978) pointed out that the weak tropical easterly jet during the 1972 summer concurred with anomalous warm sea-surface temperatures over the eastern Pacific. Tanaka (1982) argued that the strengthening of the tropical easterly jet is related to the zonalization of the midlatitude circulation over northeast Asia but in unrelated to the tropical Walker circulation. In contrast, Chen and van Loon (1987) suggested that the interannual variability of the jet is related to that of planetary-scale divergent circulation in the tropics. It thus appears that a further effort should be made to disclose the mechanism responsible for the interannual variability of the tropical easterly jet.

Using a linearized barotropic model with the specified seasonally-averaged zonal-mean wind and with the specified vortex stretching used as forcing, Holton and Colton (1972) were able to simulate the summer-time tropical stationary eddies. Apparently, the vortex stretching induced by large horizontal divergence over the Asian monsoon region is important to the existence of the Tibetan anticyclone and the tropical easterly jet. Additionally, Holton and Colton also pointed out that the vorticity generated by vortex stretching is balanced mostly by vorticity dissipation due to frictional damping, although vorticity advection does play a minor role. Later, Kang and Held (1986) employed a barotropic model to simulate the northern-summer stationary eddies produced by a full-physics general circulation model (GCM) through accounting for the horizontal vorticity advection associated with divergent flow. The zonal-mean wind and divergence of summer simulation generated by the GCM at 200 mb are used in Kang and Held's model. Kang and Held found that in contrast to Holton and Colton's simulation, their simulation of northern-summer stationary eddies is insensitive to frictional parameterization. Despite this difference, both studies agreed that the planetary-scale divergence used in the model forcing is crucial to the simulation of stationary eddies with their simple barotropic models.

Analyzing the kinetic energy budget of the tropical easterly jet, Chen and van Loon (1987) observed that divergent and convergent centers of the east-west circulation in the South-Asian monsoon region exist on the upstream and downstream sides of this jet respectively. Moreover, the kinetic energy of the tropical easterly jet generated on the upstream side is converged toward and is destroyed on the downstream side. During the weak monsoon, convergence and divergence of kinetic-energy flux on the upstream and downstream sides of this jet, respectively, are suppressed in the same way as the weakening of the monsoon divergent circulation. According to the kinetic energy budget analysis, the tropical easterly jet can be weakened when the kinetic-energy generation and destruction of this jet are reduced during weak monsoons. Thus, Chen and van Loon inferred that the interannual variation of the tropical easterly jet may be related to the interannual variation of the planetary-scale divergent circulation.

It was revealed from climatology of the tropical circulation, e.g., Newell et al. (1972), that the tropical zonal-mean easterlies exhibit a maximum value of about 8 ms^{-1} at 200 mb. On the other hand, the maximum easterly of the tropical easterly jet reaches about 25 ms^{-1}. Apparently, this jet is formed primarily by stationary eddies. The numerical simulations of stationary eddies with simple barotropic models by Holton and Colton (1972) and Kang and Held (1986) showed that the climatological component of summer eddies in the tropics can be well generated by adjusting the rotational flow to the time-mean divergent circulation. Since the vorticity source is measured by the divergence of vorticity flux associated with the divergent flow, interannual changes in the summer-mean divergent circulation should be reflected in the vorticity source. If the vorticity source of each summer is applied to a barotropic model, the interannual changes in stationary eddies are likely to emerge from their numerical simulations. This approach may, in turn, substantiate Chen and van Loon's inference that the interannual variation of the summer-mean stationary eddies responds to that of the summer-mean divergent circulation.

The argument above reveals that the divergent circulation depicted by the observational data is essential to the suggested numerical simulations for the interannual variation of stationary eddies. Based upon our recent study (Chen and Yen, 1991a), the planetary-scale divergent circulation has been reasonably well depicted by the wind data produced from the Global Data Assimilation System (GDAS) of the National Meteorological Center (NMC) in the past decade. Moreover, in that decade, the tropical easterly jet was relatively weak in three summers (1979, 1983, 1987) and particularly strong in the other two summers (1985, 1988). Thus, we have used the NMC GDAS data of the past decade to perform the diagnostic analysis of the stationary-eddy streamfunction in this study. Based upon this budget analysis, we shed some light on the effect of planetary-scale divergent circulation on the interannual variation of stationary eddies associated with the tropical easterly jet. We have also adopted a diagnostic barotropic model to simulate this interannual variation with the observed vorticity source and to substantiate the diagnostic finding.

2. Interannual variation in divergent circulation and outgoing long-wave radiation during northern summers

Following Chen and van Loon (1987), we use the area-mean kinetic energy at 200 mb for eleven summers (1979–1989) over the region (5° S–20° N, 30° W–180° E), which accommodates most of the tropical easterly jet as an indicator of this jet's intensity. The area-mean kinetic energy of this region (Fig. 1) reveals that the tropical easterly jet was relatively weak in the summers of 1979, 1983, and 1987 and particularly strong in the summers of 1985 and 1988. Of the summers with a weak tropical easterly jet, 1983 and 1987 are those after the El Niño-Southern Oscillation (ENSO) warm events. The summer of 1979 did not follow an ENSO event, but a severe drought occurred over the Indian monsoon region. Of the summers with a strong tropical easterly jet, sea-surface temperatures and convection activity over the westernmost tropical Pacific increased in only 1985. Although the monsoon rainfall did not reach its climatological level in this summer, the Indian monsoon circulation was significantly strengthened. In addition to the intensification of the Indian monsoon in the 1988 summer, the monsoon rainfall of this summer also greatly exceeded its normal amount. In our analysis, we observed that the summer-mean velocity potential ($\bar{\chi}$) of the NMC GDAS was not well assimilated for the 1983 summer. Because the upper-level divergent circulations during the weak and strong easterly jet will be contrasted to explore the possible mechanism

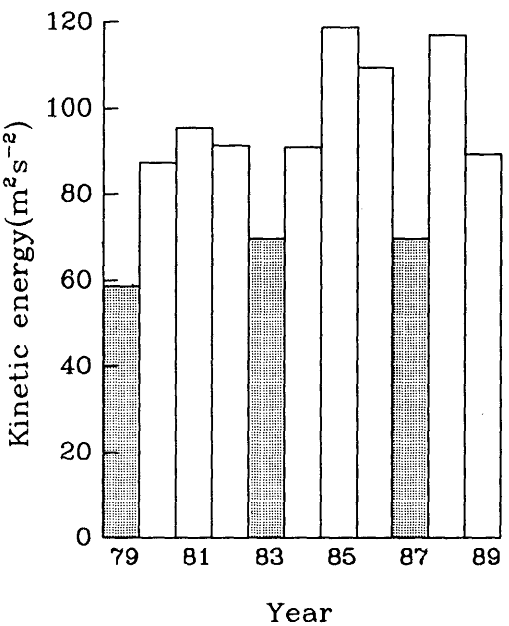

Fig. 1. Histogram of the area-averaged kinetic energy at 200 mb over the region (5° S–20° N, 30° W–150° E) accommodating the tropical easterly jet. The kinetic energies of the 1979, 1983, and 1987 summers are shaded.

responsible for the interannual variation of stationary eddies during the northern summers, we exclude the 1983 summer in this study. In addition, because we shall only focus on the 200-mb level, all variables concerned in this study hereafter refer to this particular level.

The multiple-summer mean eddy velocity potential $\bar{\chi}_E$ (Fig. 2a) exhibits a well-portrayed wavenumber-1 structure with a divergent center located over the western Pacific and a convergent center located over the coast of western Africa. As will be discussed later, the interannual variation of the stationary-eddy streamfunction $\bar{\psi}_E$ may be induced by that of the planetary-scale divergent circulation. Thus, let us first examine the interannual variation of eddy divergent circulation during summers of weak and strong tropical easterly jets. For convenience, the interannual variation of eddy divergent circulation is denoted by $\Delta\bar{\chi}_E(n) = \bar{\chi}_E(n) - \bar{\chi}_E$, where n represents a given year. Regardless of their structures, $\Delta\bar{\chi}_E(79)$ and $\Delta\bar{\chi}_E(87)$ display a common pattern resembling $\bar{\chi}_E$ but are opposite in sign. This contrast indicates that the planetary-scale divergent circulation was weakened in the two summers of the weak tropical easterly jet. In contrast, the wavenumber-1 structure of $\Delta\bar{\chi}_E(85)$ resembles that of $\bar{\chi}_E$. Apparently, the planetary-scale asymmetric divergent circulation was intensified in this summer. The spatial structure of $\Delta\bar{\chi}_E(88)$ is strangely in quadrature with that of $\bar{\chi}_E$. This quadrature relation not only intensifies the divergent center over the western Pacific, but it also weakens the convergent center over the eastern Atlantic. This interannual change in $\bar{\chi}_E$ during the 1988 summer moves these two centers somewhat westward, as shown in Haskins et al. (1989).

It was shown by Kasahara's (1982) analytic study and Chen and Baker's (1987) diagnostic analysis that tropical diabatic heating is more or less balanced by adiabatic cooling (i.e., $-\sigma\omega \simeq (1/C_p)\,\dot{Q}$, where σ is static stability, ω vertical velocity, C_p specific heat with constant pressure and $\dot{Q}$ diabatic heating). The ω field is an integral part of the 3-dimensional divergent circulation. Conceivably, any change in tropical diabatic heating should be reflected in divergent circulation. Thus, the weakening and intensification of the planetary-scale divergent circulation during summers of the weak and strong tropical easterly jet, respectively, might be attributed to the inter-

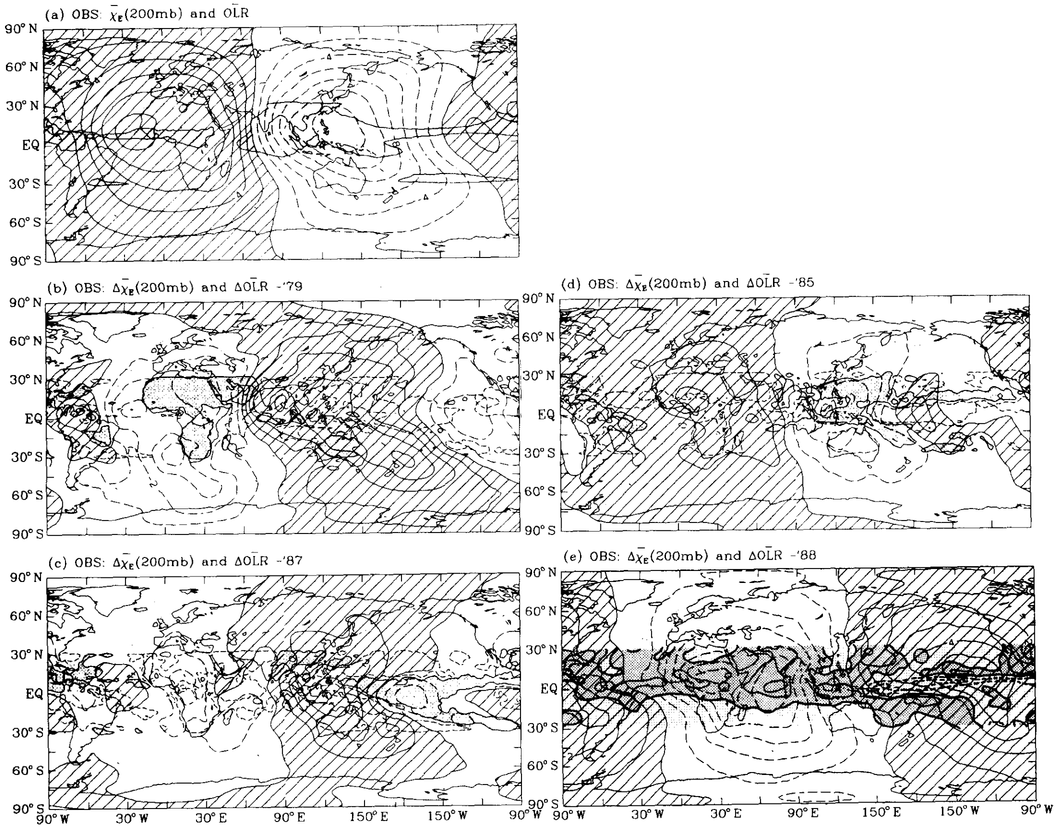

Fig. 2. (a) The climatological summer-mean (79–82 and 84–89) planetary-scale velocity potential $\bar{\chi}_E$ at 200 mb and the climatological summer-mean (79–89) outgoing longwave radiation $\overline{OLR} \leqslant 240$ Wm^{-2} (shaded area), (b) $\Delta\bar{\chi}_E(79)$ and $\Delta\overline{OLR}(79)$, (c) $\Delta\bar{\chi}_E(87)$ and $\Delta\overline{OLR}(87)$, (d) $\Delta\bar{\chi}_E(85)$ and $\Delta\overline{OLR}(85)$, and (e) $\Delta\bar{\chi}_E(88)$ and $\Delta\overline{OLR}(88)$. The positive values of $\bar{\chi}_E$ and $\Delta\bar{\chi}_E$ are hatched. In (a) the $\overline{OLR}$ values $\leqslant 240$ wm^{-2} and in (b)–(d) $\Delta\overline{OLR} \leqslant 240$ Wm^{-2} and $\Delta\overline{OLR} \leqslant -4$ Wm^{-2} are heavily shaded, while $\Delta\overline{OLR} \geqslant 4$ wm^{-2} is lightly shaded. $\Delta\overline{OLR}(88)$ compiled by Ropelewski (1988) is used here. The positive (negative) $\Delta\overline{OLR}(88)$ values are lightly (heavily) shaded and the contour interval of $\Delta\overline{OLR}(88)$ is 10 Wm^{-2}. The contour intervals of $\bar{\chi}_E$ and $\Delta\bar{\chi}_E$ are 2×10^6 m^2 s^{-1} and 1×10^6 m^2 s^{-1}, respectively.

annual variation of tropical diabatic heating. The latent heat released by cumulus convection contributes a major part of tropical diabatic heating. The interannual variation of tropical diabatic heating can be well indicated by $\Delta\overline{OLR}(n)$ [$= \overline{OLR}(n) - \overline{OLR}$], where $\overline{OLR}$ is the multiple-summer mean and is shown in Fig. 2a with values smaller than 240 wm^{-2} heavily shaded. Note that the OLR data of 1988 July were missing in the data archive of the National Center for Atmospheric Research. Therefore $\Delta\overline{OLR}(88)$ reported by Ropelewski (1988, his Fig. 5b) is used in this study. Additionally, we analyzed only the OLR data between 30° S and 30° N in this study.

$\Delta\overline{OLR}(n) \geqslant 4$ ($\leqslant -4$) Wm^{-2} is lightly (heavily) shaded in Figs. 2b–d. Centers of positive $\Delta\overline{OLR}(79)$ and $\Delta\overline{OLR}(87)$, located over centers of positive $\Delta\bar{\chi}_E(79)$ and $\Delta\bar{\chi}_E(87)$, coincide with the major negative $\overline{OLR}$ center over the South Asian monsoon region. The contrast between $\overline{OLR}$ and $\Delta\overline{OLR}(n)$ reveals that cumulus convection over the Asian monsoon region and the western Pacific was suppressed during summers of the weak tropical easterly jet. In contrast, the negative

$\Delta\overline{\mathrm{OLR}}(85)$ center appears in the western Pacific, and the negative $\Delta\overline{\mathrm{OLR}}(88)$ values (heavily shaded) cover not only the western Pacific but also most of the tropical belt, with the exception of the Pacific sector. Apparently, the convection activity over the western Pacific or the monsoon region was enhanced during summers of the strong easterly jet, as was the planetary-scale divergent circulation. In short, the interannual variation of planetary-scale divergent circulation is relatively consistent with that of the tropical convection activity. This consistency supports the previous suggestion that the interannual variation of planetary-scale divergent circulation results from that of tropical diabatic heating.

3. The stationary-eddy streamfunction budget during northern summers

To examine diagnostically the effect of divergent circulation on the stationary eddies, we adopt the streamfunction budget analysis (Kang and Held, 1986; Chen and Chen, 1990). The streamfunction (ψ) budget of stationary eddies may be written as

$$
\begin{aligned}
0 = {} & \underbrace{\nabla^{-2}[-\bar{V}_\psi \cdot \nabla(f+\bar{\zeta})]_E}_{\bar{\psi}_{AVE}} \\
& + \underbrace{\nabla^{-2}\{-\nabla \cdot [\bar{V}_\chi (f+\bar{\zeta})]_E\}}_{\bar{\psi}_{\chi E}} \\
& + \underbrace{\nabla^{-2}[-\nabla \cdot \overline{(V'\zeta')}]_E}_{\bar{\psi}_{tsE}} + \underbrace{\nabla^{-2} F_E}_{\bar{\psi}_{FE}}, \qquad (1)
\end{aligned}
$$

where V, V_ψ, and V_χ are total, rotational, and divergent wind vectors, respectively, and F includes vertical advection, twisting, and dissipation of vorticity. $\overline{(\ )}$ = summer mean, and $(\ )' = (\ ) - \overline{(\ )}$. $(\ )_E$ is the eddy component of $(\ )$ and $(\ )_E = (\ ) - (\ )_Z$, where $(\ )_Z$ is the zonal mean of $(\ )$, and ∇^{-2} is the inverse Laplacian. Notice that the vortex stretching term and the vorticity advection by the divergent wind are combined together in (1) to form the horizontal divergence of vorticity flux by the divergent wind. This divergence of vorticity flux is regarded as the vorticity source in this study and is equivalent to the Rossby-wave source of Sandeshmukh and Hoskins (1988). In order to explore the maintenance of stationary eddies with the streamfunction budget, let us split all variables into their zonal and eddy components. (1) may be written as:

$$
\begin{aligned}
0 = {} & \underbrace{\nabla^{-2}\left(-\bar{u}_{\psi Z}\frac{\partial \bar{\zeta}_E}{\partial x}\right)}_{\bar{\psi}_{AVE_1}} + \underbrace{\nabla^{-2}(-\beta \bar{v}_{\psi E})}_{\bar{\psi}_{AVE_2}} \\
& + \underbrace{\nabla^{-2}\left(-\bar{v}_{\psi E}\frac{\partial \bar{\zeta}_Z}{\partial y}\right)}_{\bar{\psi}_{AVE_3}} + \underbrace{\nabla^{-2}(-\bar{V}_{\psi E} \cdot \nabla \bar{\zeta}_E)_E}_{\bar{\psi}_{AVE_4}} \\
& + \underbrace{\nabla^{-2}(-f \nabla \cdot \bar{V}_{\chi E})}_{\bar{\psi}_{\chi E_1}} + \underbrace{\nabla^{-2}(-\bar{v}_{\chi E}\beta)}_{\bar{\psi}_{\chi E_2}} \\
& + \underbrace{\nabla^{-2}[-\nabla \cdot (\bar{V}_{\chi E}\bar{\zeta} + \bar{v}_{\chi Z}\bar{\zeta}_E)_E]}_{\bar{\psi}_{\chi E_3}} \\
& + \underbrace{\nabla^{-2}[-\nabla \cdot \overline{(V'\zeta')}_E]}_{\bar{\psi}_{tsE}} + \underbrace{\nabla^{-2}\bar{F}_E}_{\bar{\psi}_{F_E}} \qquad (2)
\end{aligned}
$$

Analyzing the stationary-eddy streamfunction (ψ_E) budget of the winter climate simulation by the community climate model of the National Center for Atmospheric Research, Chen and Chen (1990) obtained the following approximation by neglecting insignificant terms:

$$\bar{\psi}_{AVE_1} + \bar{\psi}_{AVE_2} + \bar{\psi}_{\chi E_1} + \bar{\psi}_{\chi E_2} \simeq 0. \qquad (3)$$

For the northern summer, Kang and Held (1986) showed that $\bar{\psi}_{\chi E_3}$ and $\bar{\psi}_{tsE}$ are small in their magnitudes over most of the globe, except in the vicinity of the Tibetan high. Our diagnostic computation of (2) with the NMC GDAS summer data is consistent with Kang and Held's finding. Furthermore, we also found that both $\bar{\psi}_{AVE_3}$ and $\bar{\psi}_{AVE_4}$ are much smaller in magnitude than $\bar{\psi}_{AVE_1}$ and $\bar{\psi}_{AVE_2}$ during the northern summer. In this season, it thus appears that the approximation (3) is legitimate.

Based upon the argument above, $\bar{\psi}_{\chi E}$ in (1) can be approximated by $\bar{\psi}_{\chi E_1} + \bar{\psi}_{\chi E_2} = \nabla^{-2}[-\nabla \cdot (f\bar{V}_{\chi E})] \simeq \bar{\psi}_{\chi E}$. The interannual variation of the summer-mean planetary-scale divergent circulation is likely to induce that of stationary eddies through the forcing $\bar{\psi}_{\chi E_1} + \bar{\psi}_{\chi E_2}$. To illustrate diagnostically this possible interaction between $\bar{\chi}_E$ and $\bar{\psi}_E$, we performed the $\bar{\psi}_E$ budget analysis for the summers of 1979–1989, except for the 1983 summer. Displayed in Fig. 3a is the multiple-summer mean $\bar{\psi}_{\chi E}$ field, whose cellular structure is spatially in quadrature along the longitudinal direction with the multiple-summer mean stationary eddies $\bar{\psi}_E$ (Fig. 4a). Note that f is only a function of latitude. Thus, we expect that the planetary-scale divergent circulation through $\bar{V}_{\chi E}$ $(=\nabla\bar{\chi}_E)$ is the primary determinant of the spatial structure of $\bar{\psi}_{\chi E} \simeq \bar{\psi}_{\chi E_1} + \bar{\psi}_{E_2} = \nabla^{-2}[-\nabla\cdot(\bar{V}_{\chi E} f)]$.

Interannual changes of $\bar{\psi}_{\chi E}$, $\Delta\bar{\psi}_{\chi E}(n)[=\bar{\psi}_{\chi E}(n) - \bar{\psi}_{\chi E}]$, in the four summers of 1979, 1985, 1987, and 1988 are shown in Figs. 3b–e, respectively. Both $\Delta\bar{\psi}_{\chi E}(79)$ and $\Delta\bar{\psi}_{\chi E}(87)$ exhibit a structure similar to $\bar{\psi}_{\chi E}$ (Fig. 3a) but are opposite in sign. This contrast indicates that $\bar{\psi}_{\chi E}$ was weakened in these two summers much the same as was the planetary-scale divergent circulation (Figs. 2b–c). In contrast, $\Delta\bar{\psi}_{\chi E}(85)$ coincides with $\bar{\psi}_{\chi E}$ in its spatial structure, and $\Delta\bar{\psi}_{\chi E}(88)$ shifts somewhat westward much the same as $\Delta\chi_E(88)$ does. So apparently, the interannual variations of planetary-scale divergent circulation in the summers of 1985 and 1988 enhanced $\bar{\psi}_{\chi E}$. It was revealed from our diagnostic analysis that both $\bar{\psi}_{tSE}$ and $\bar{\psi}_{FE}$ (not shown) are much smaller in magnitude than $\bar{\psi}_{\chi E}$ and $\bar{\psi}_{AVE}$, and $\bar{\psi}_{\chi E}$ and $\bar{\psi}_{AVE}$ more or less counterbalance each other as expected in (1). Based upon the counterbalance relation between $\bar{\psi}_{AVE}$ and $\bar{\psi}_{\chi E}$, the weakening of $\bar{\psi}_{AVE}$ (not shown) in the summers of 1979 and 1987 must have responded to that of $\bar{\psi}_{\chi E}$ in these two summers. The *reversed* situation occurred in the summers of 1985 and 1988.

It was found from the summer $\bar{\psi}_E$ budget analysis of this study that $\bar{\psi}_{AVE}$ can be approximated by $\bar{\psi}_{AVE_1} + \bar{\psi}_{AVE_2}$ as suggested in (3). Both $\bar{\psi}_{AVE_1}$ and $\bar{\psi}_{AVE_2}$ are derived from the linear terms

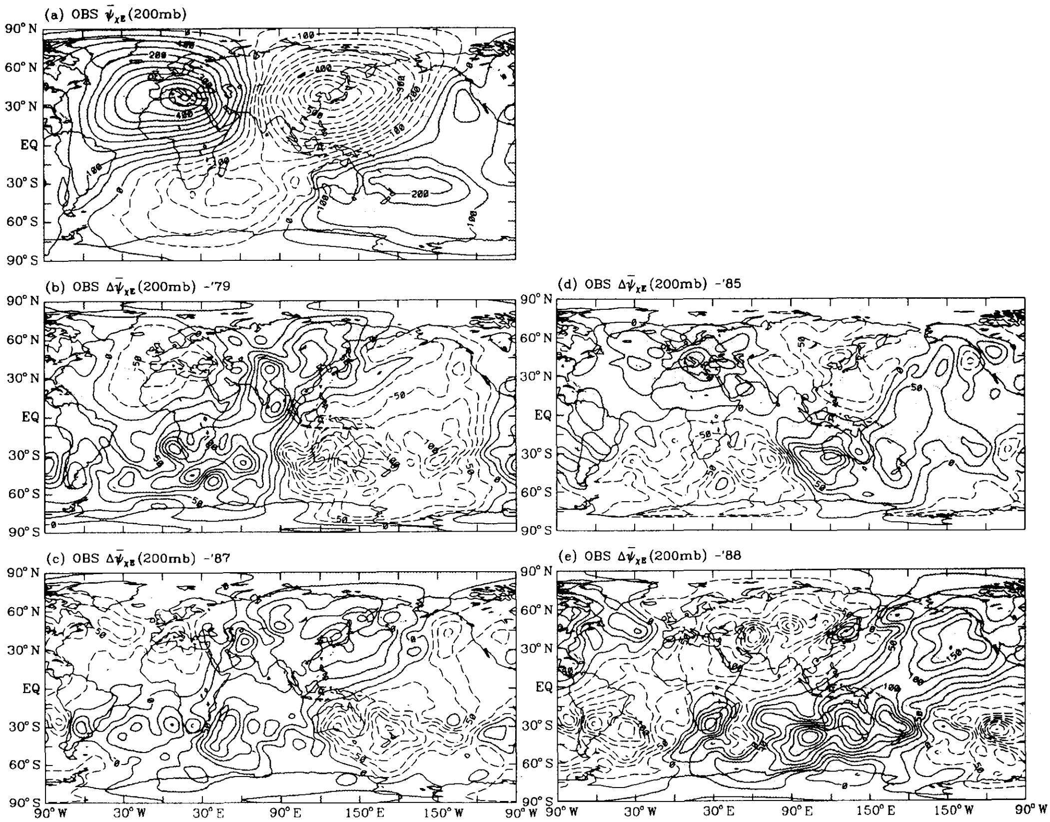

Fig. 3. Same as Fig. 2, except for $\bar{\psi}_{\chi E}$ and $\Delta\bar{\psi}_{\chi E}$. The contour intervals of $\bar{\psi}_{\chi E}$ and $\Delta\bar{\psi}_{\chi E}$ are 50 $m^2 s^{-2}$ and 25 $m^2 s^{-2}$, respectively.

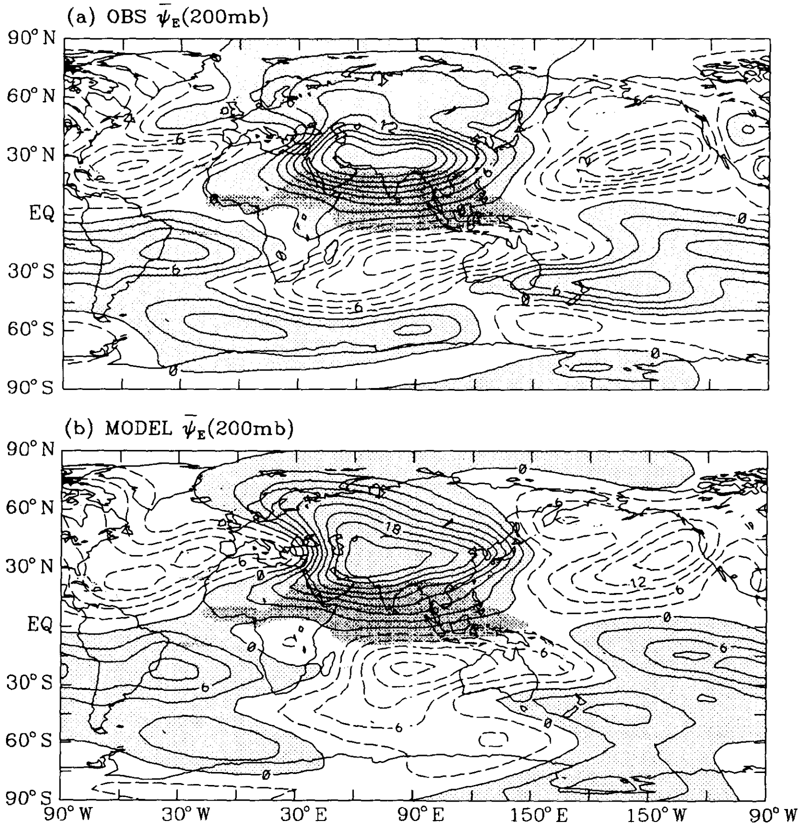

Fig. 4. (a) The climatological summer-mean (1979–1989) with the observed $\bar{\psi}_E$ at 200 mb, and (b) the simulated climatological $\bar{\psi}_E$. The positive values of $\bar{\psi}_E$ are lightly shaded, and the tropical easterlies with the wind speed larger than 10 ms^{-1} are heavily shaded. The contour interval of $\bar{\psi}_E$ is $3 \times 10^6\ m^2\ s^{-1}$.

of horizontal vorticity advection by rotational wind. If $\bar{\psi}_E$ is sinusoidal, we are able to find the relation $\bar{\psi}_{AVE_1} + \bar{\psi}_{AVE_2} \sim -i\bar{\psi}_E$, where $i = \sqrt{-1}$. It is inferred from this mathematical relation that a spatial quadrature relation exists between $\bar{\psi}_E$ and $\bar{\psi}_{AVE_1} + \bar{\psi}_{AVE_2}$. Thus $\bar{\psi}_E$ should undergo interannual variation as $\bar{\psi}_{AVE}$ does. In order to substantiate this argument, we need to find out the relation between the interannual variations of $\bar{\psi}_E$ and $\bar{\psi}_{AVE}$ in our $\bar{\psi}_E$ budget analysis.

The multiple-summer mean eddy streamfunction $\bar{\psi}_E$ field (Fig. 4a) contains the Tibetan high to the north and the westward extension of the Australian anticyclone over the Indian Ocean to the south of the tropical easterly jet. This jet is indicated by having isotachs larger than 10 ms^{-1} heavily shaded (its core reaches about 25 ms^{-1}.) $\Delta\bar{\psi}_E(79)$ (Fig. 5a) exhibits sign opposite to $\bar{\psi}_E$ over most parts of the tropical easterly jet, while $\Delta\bar{\psi}_E(87)$ (Fig. 5c) shows sign opposite to $\bar{\psi}_E$ to the eastern half of the jet. These sign changes imply that a part of the two monsoon anticyclones was weakened and so was part of the tropical easterly jet during the summers of 1979 and 1987. The wind speed reduction of this jet larger than 2 ms^{-1} is heavily shaded in Figs. 5a and 5c. Actually, the maximum reduction in the wind speed of this jet exceeded 8 ms^{-1} in the 1979 summer and was close to 6 ms^{-1} in the 1987 summer, although locations of the wind speed reduction differ between these two summers. $\Delta\bar{\psi}_E(85)$ (Fig. 6a) in the monsoon region exhibits a pattern similar to $\bar{\psi}_E$, but part of $\Delta\bar{\psi}_E(88)$ over the Asian continent is opposite is sign from $\bar{\psi}_E$. Nevertheless, the

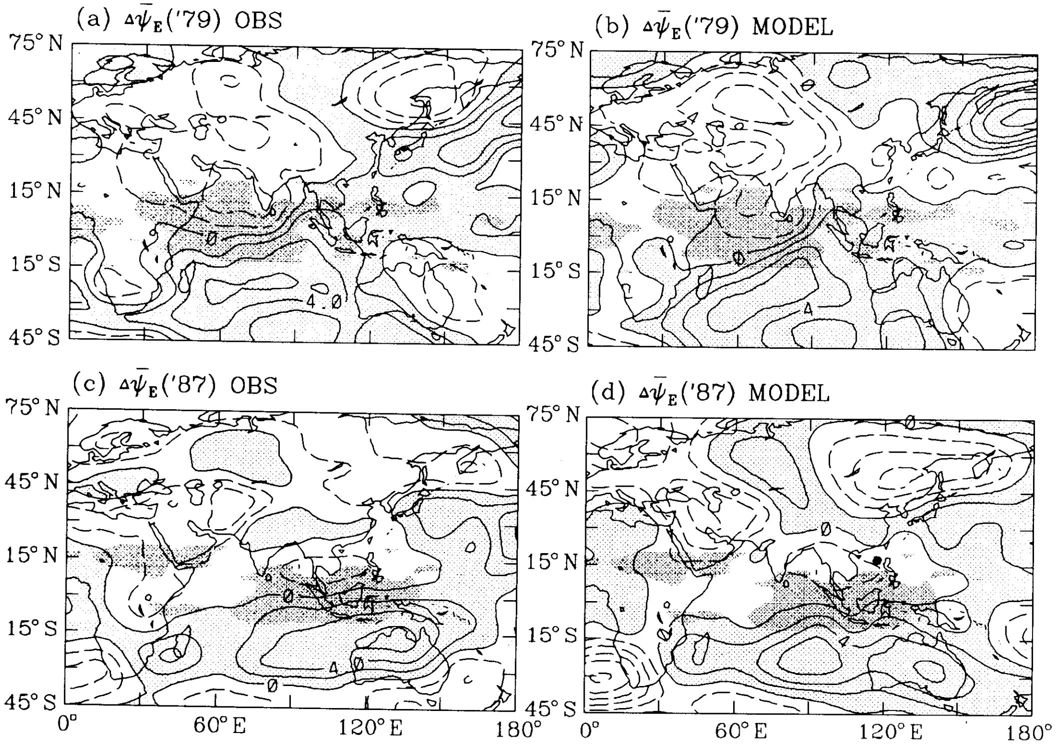

Fig. 5. (a) Observed $\Delta\bar{\psi}_E(79)$ $[=\bar{\psi}_E(79)-\bar{\psi}_E]$ at 200 mb, (b) simulated $\Delta\bar{\psi}_E(79)$, (c) observed $\Delta\bar{\psi}_E(87)$ $[=\bar{\psi}_E(87)-\bar{\psi}_E]$ at 200 mb and, (d) simulated $\Delta\bar{\psi}_E(87)$. The positive values of $\Delta\bar{\psi}_E$ are lightly shaded. The wind speed reduction of the tropical easterly jet larger than 2 ms^{-1} is heavily shaded. The contour interval of $\Delta\bar{\psi}_E$ is 2×10^6 m^2 s^{-1}.

tropical easterly jet was strengthened throughout its course in the 1985 summer and in its western half in the 1988 summer, as indicated by heavily shaded areas (larger than 2 ms^{-1}) in Figs. 6a and 6c, respectively. The maximum increase of the jet speed was about 7 and 10 ms^{-1} for the summers of 1985 and 1988, respectively.

The aforementioned quadrature relationship between $\bar{\psi}_E$ and $\bar{\psi}_{AVE}$ can be realized by contrasting $\bar{\psi}_E$ (Fig. 4a) and $\bar{\psi}_{\chi E}$ (Fig. 3a), because $\bar{\psi}_{\chi E}$ and $\bar{\psi}_{AVE}$ almost compensate for each other. Conceivably, this spatial quadrature relation is also expected between $\Delta\bar{\psi}_E(n)$ and $\Delta\bar{\psi}_{AVE}(n)$, as that exists between $\Delta\bar{\psi}_E(n)$ and $\Delta\bar{\psi}_{\chi E}(n)$. The comparison between observed $\Delta\bar{\psi}_E(n)$ (Figs. 5a and 5c, and Figs. 6a and 6c) and observed $\Delta\bar{\psi}_{\chi E}(n)$ (Figs. 3b–e) supports our argument here. Because the interannual variations of $\bar{\psi}_{\chi E}$ in the past decade follow closely those of the planetary-scale divergent circulation $\bar{\chi}_E$ (Fig. 2), the interannual variation of $\bar{\psi}_E$ and that of $\bar{\chi}_E$ are likely linked through that of $\bar{\psi}_{\chi E}$.

4. Numerical simulation of summer stationary eddies

As inferred diagnostically from the $\bar{\psi}_E$ budget analysis presented in the last section, interannual variations of stationary eddies in the northern summer may be related to those of the planetary-scale divergent circulation and tropical diabatic heating through the adjustment between interannual variations of $\bar{\psi}_{\chi E}$ and $\bar{\psi}_{AVE}$. However, to substantiate this inference, a numerical simulation is in order. Based upon (2) and (3), a global barotropic model with a specified forcing would serve the purpose. In this study, we adopt the

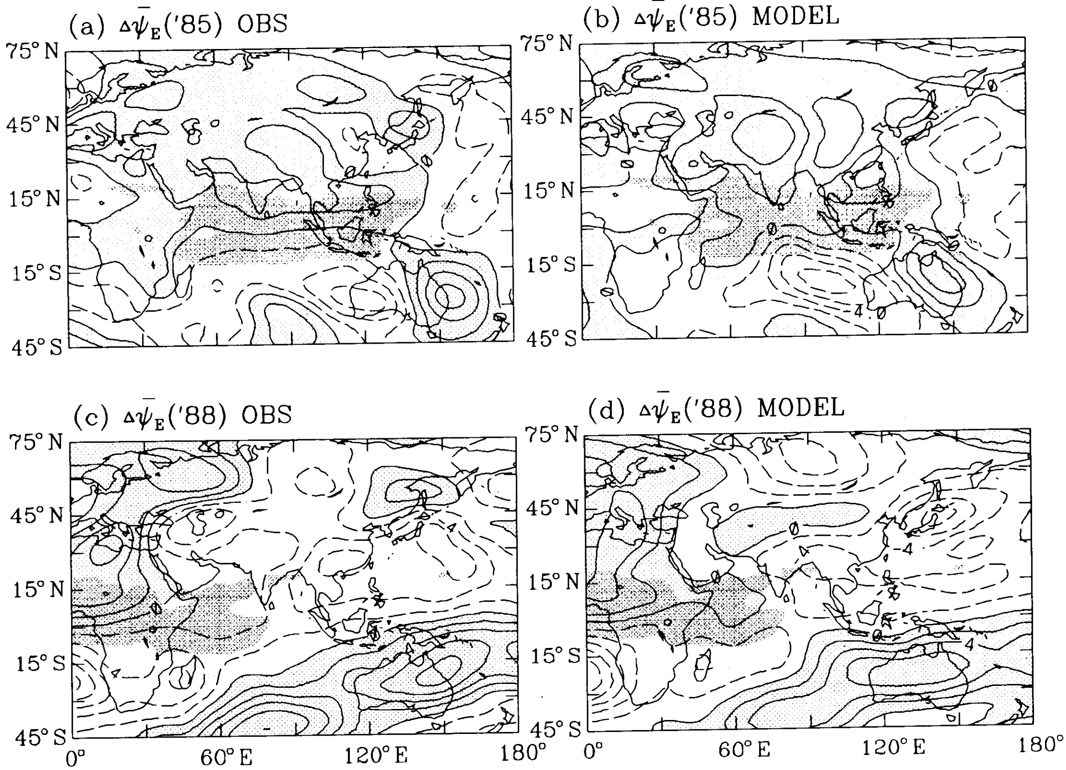

Fig. 6. Same as Fig. 5, except for the summers of 1985 and 1988. The wind speed increase of the tropical easterly jet larger than 2 ms^{-1} is heavily shaded.

model developed by Branstator (1983, 1984) to simulate the multiple-summer mean stationary eddies and the stationary eddies of summers with either the weak or strong tropical easterly jet (with the diagnostically computed $\nabla^2\bar{\psi}_{\chi E}$ used as forcing).

Neglecting some insignificant terms, the model is formulated with the vorticity equation on a sphere, as expressed in (2)

$$\frac{\bar{u}_{\psi Z}}{a\cos\varphi}\frac{\partial}{\partial\lambda}\nabla^2\bar{\psi}_E+\left[f-\frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}(\bar{u}_{\psi Z}\cos\varphi)\right]$$

$$\times\frac{\partial}{a\cos\varphi}\frac{\partial\bar{\psi}_E}{\partial\lambda}=\bar{R}-\alpha\nabla^2\bar{\psi}_E-\varepsilon\nabla^6\bar{\psi}_E, \qquad (4)$$

where a is the earth's radius, λ longitude, and φ latitude. α ($=1.57\times10^{-6}\,s^{-1}\sim7\,day^{-1}$) and ε ($=2.34\times10^{16}\,m^4\,s^{-1}$) are drag and diffusion coefficients, respectively. $\bar{R}$ is a forcing which should be either the multiple summer-mean ($\bar{R}_M$), 79($\bar{R}_{79}$)-, 85($\bar{R}_{85}$)-, 87($\bar{R}_{87}$)-, or 88($\bar{R}_{88}$)-summer $\nabla^2\bar{\psi}_{\chi E}$ fields. In order to solve (4), $\bar{\psi}_E$ and $\bar{R}$ are expressed in terms of spherical harmonics with a 20-wave triangular truncation. Readers may refer to Branstator (1983) for mathematical and numerical details of this model.

The zonal mean winds, $\bar{u}_{\psi Z}$, used in numerical simulations are shown in Fig. 7. As revealed from this figure, $\bar{u}_{\psi Z}(n)'s$ do not differ too much from the multiple summer mean $\bar{u}_{\psi ZM}$ (solid line), except in the high latitudes of both hemispheres. In the tropics, the difference between $\bar{u}_{\psi ZM}$ and $\bar{u}_{\psi Z}(n)$ for summers with either the weak or strong tropical easterly jet is within the range of 1.5 ms^{-1}. Thus, it is evident that the interannual variations

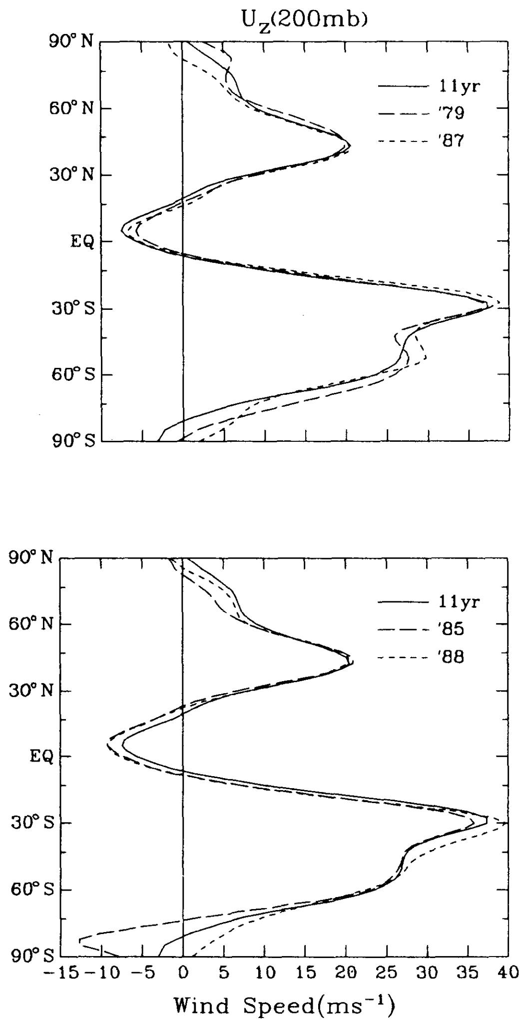

Fig. 7. Latitudinal profiles of the zonal-mean wind $\bar{u}_{\psi Z}$ (200 mb) for the climatological mean of 11 summers (1979–1989) and for the summers of 1979, 1985, 1987, and 1988.

of $\bar{u}_{\psi Z}$ in the tropics are much smaller than those of the tropical easterly jet. In other words, the interannual variations of the tropical easterly jet are essentially caused by those of stationary eddies.

The major goal of the numerical simulation is to use the forced barotropic model to examine the response of summer stationary eddies (particularly the two monsoon anticyclones associated with the tropical easterly jet) to interannual changes in tropical forcing $\bar{R}_n$. First, let us explore the model performances in simulating the climatological summer-mean stationary eddies. Besides the two monsoon anticyclones, oceanic troughs over the Pacific and the Atlantic of both hemispheres are well depicted by the observed $\bar{\psi}_E$ field (Fig. 4a). As shown in Fig. 4b, these salient features of the summer-mean upper tropical circulation are well simulated by the model with the climatological zonal-mean wind $\bar{u}_{\psi ZM}$ and forcing $\bar{R}_M$, except in the high latitudes of both hemispheres. This discrepancy between model simulation and observation is perhaps caused by some forcing missed in high latitudes of the model. However, in view of the fine control simulation of climatological stationary eddies in the summer tropics, it may be fair to claim that the major features of the upper tropical circulation are generated locally by the tropical forcing. Because this study mainly focuses on the tropical region, we choose not to make any adjustment on the model forcing in high latitudes so that we can faithfully maintain the response of the model to the forcing computed directly with the NMC GDAS data.

The effect of interannual changes of the planetary-scale divergent circulation on stationary eddies is illustrated in terms of model $\Delta\bar{\psi}_E(n)$ [=model $\bar{\psi}_E(n)$-control simulation $\bar{\psi}_E$], which is verified by observational $\Delta\bar{\psi}_E(n)$ [=observational $\bar{\psi}_E(n)-\bar{\psi}_E$]. Model $\Delta\bar{\psi}_E(n)'s$ are displayed in Figs. 5b and 5d for summers of the weak tropical easterly jet and in Figs. 6b and 6d for summers of the strong easterly jet. Certainly, it is an excessive demand for such a simple barotropic model used in this study to reproduce every detail of observational $\Delta\bar{\psi}_E(n)'s$. In fact, as revealed from the contrast between model and observational $\Delta\bar{\psi}_E(n)'s$ in both Figs. 5 and 6, interannual variations of the two monsoon anticyclones are surprisingly well simulated by the model. Based upon the diagnostic analysis of the $\bar{\psi}_E$ budget, it was hypothesized that interannual changes in the summer planetary-scale divergent circulation cause those in stationary eddies through the forcing $\bar{\psi}_{\chi E}$. The resemblance between model and observational $\Delta\bar{\psi}_E(n)'s$ substantiates this hypothesis. It was pointed out that the tropical easterly jet is a part of stationary eddies over the monsoon region. Apparently the interannual changes of this jet follows those of the northern-summer stationary eddies. Thus, any mechanism causing interannual changes of stationary eddies over the monsoon region should be responsible for interannual changes of the tropical easterly jet. The numerical simulation of $\Delta\bar{\psi}_E(n)$ presented above supports the argument that interannual variations of the tropical easterly jet are related to those of planetary-scale divergent circulation.

Finally, one more comment should be made regarding the effect of interannual variations of $\bar{u}_{\psi Z}(n)$ on those of stationary eddies. As pointed out previously, interannual changes in $\bar{u}_{\psi Z}(n)$ of the two extreme cases (the weak and strong tropical easterly jet) are within 1.5 ms^{-1} in the tropics. We also performed simulations of $\bar{\psi}_E(n)$ for all four summers in this study with climatological zonal-mean wind $\bar{u}_{\psi ZM}$. Model $\Delta\bar{\psi}_E(n)'s$ obtained from these simulations (not shown) resemble those shown in Figs. 5 and 6. In other words, the minor interannual changes in $\bar{u}_{\psi Z}(n)$ shown in Fig. 7 do not significantly affect the model response to forcing $\bar{R}_n$'s.

5. Concluding remarks

Although the maximum easterly of the 200-mb climatological zonal wind in the tropics is about 8 ms^{-1} (Fig. 7), the core of the tropical easterly jet reaches about 25 ms^{-1}. Apparently, stationary eddies are responsible for the existence of the tropical easterly jet. Previous studies, e.g., Kobayashi (1974), Chen and van Loon (1987), and others, have observed that this jet undergoes a significant interannual variation. In the past decade, the tropical easterly jet was significantly weakened in the summers of 1979, 1983, and 1987, and was significantly strengthened in the summers of 1985 and 1988. As compared to long-term climatology, the maximum zonal-mean easterly at 200 mb of these two groups of summers changed only within a range of 1.5 ms^{-1}. The maximum reduction or increase in the wind speed of the tropical easterly jet was about 6–10 ms^{-1}. It thus appears that the interannual variation of the tropical easterly jet is caused mainly by that of stationary eddies associated with the Tibetan high and the westward extension of the Australian anticyclone. Notice that we did not include the 1983 summer in our further analysis because we felt that the upper divergent circulation in this summer was not well assimilated in the NMC GDAS.

It was revealed from our diagnostic analysis of the stationary-eddy streamfunction ($\bar{\psi}_E$) budget analysis that $\bar{\psi}_E$ is maintained by the counterbalance between two physical processes: streamfunction responses to horizontal vorticity advection ($\bar{\psi}_{AVE}$) and divergence of vorticity flux associated with divergent flow ($\bar{\psi}_{\chi E}$). It was also observed that $\bar{\psi}_{\chi E}$ $[\simeq\nabla^{-2}\{-\nabla\cdot(f\bar{V}_{\chi E})\}]$ is primarily determined by the planetary-scale divergent circulation through $\bar{V}_{\chi E}$ $(=\nabla\bar{\chi}_E)$. The linearized vorticity equation reveals the relation $\bar{\psi}_{AVE}\sim -i\bar{\psi}_E$. Undoubtedly, interannual changes in $\bar{\psi}_{\chi E}$ are decisively affected by those of $\bar{V}_{\chi E}$, i.e., interannual changes in the planetary-scale divergent circulation. In turn, the counterbalance between $\bar{\psi}_{AVE}$ and $\bar{\psi}_{\chi E}$ and the spatial quadrature relation between $\bar{\psi}_{AVE}$ and $\bar{\psi}_E$ indicate that interannual variations of $\bar{\psi}_E$ are caused by those of divergent circulation. Analyzing the $\bar{\psi}_E$ budget with the 200-mb wind of the summers from 1979 to 1989 (generated by the Global Data Assimilation System of the National Meteorological Center), we found that $\bar{\chi}_E$, $\bar{\psi}_{\chi E}$, and $\bar{\psi}_E$ associated with the two monsoon anticyclones in the upper troposphere and the tropical easterly jet were weakened in the summers of 1979 and 1987 and were strengthened in the summers of 1985 and 1988. The interannual changes in the $\bar{\psi}_E$ budget support the argument that interannual variations of the tropical easterly jet are induced by those of the planetary-scale divergent circulation. This inference derived from the diagnostic analysis of the $\bar{\psi}_E$ budget was further substantiated by numerical simulations of the summer stationary eddies with a simple forced barotropic model. In this model, the zonal-mean wind and the forcing $\nabla^2\bar{\psi}_{\chi E}$ of the multiple-summer climatology and the summers of 1979, 1985, 1987, and 1988 were specified.

It was illustrated by Chen and Yen (1991a) through a velocity-potential (χ) maintenance equation that the tropical diabatic heating is a vital factor maintaining planetary-scale divergent circulation. It is likely that the interannual variation of tropical diabatic heating causes that of planetary-scale divergent circulation. If this argument is true, the link implied in this study between interannual variations of the tropical diabatic heating and those of the tropical easterly jet through divergent circulation may be the possible cause of the latter interannual variation. Since the major tropical diabatic heating is derived from the latent heat released by cumulus convection, we also analyzed interannual changes in the outgoing longwave radiation (OLR) data, $\Delta\overline{\mathrm{OLR}}(n)$, in the tropics for the summers of 1979, 1985, 1987, and 1988. We found that centers of $\Delta\overline{\mathrm{OLR}}(n)$ and $\Delta\bar{\chi}_E(n)$ coincide, particularly over the Pacific. The suggested link between interannual variation of tropical diabatic heating and that of the tropical easterly jet is further supported by this coincidence.

Based upon rainfall climatology, Koteswaram (1958) pointed out that a rainbelt exists north of the axis of the tropical easterly jet east of the Indian subcontinent, and that another rain area is located over the region south of the jet in Africa. In spite of the interrelation between the tropical easterly jet and the Indian monsoon, the interannual variation of the tropical easterly jet definitely affects the regional weather on both the upstream side over southeast Asia and the downstream side over Africa. Lau and Li (1984) illustrated the transition of upper Asian circulation and the northward migration of the East Asian monsoon rainbelt, i.e., the Mei-Yü front. Recently, Chen and Yen (1991b) showed that the central African anticyclone can be modulated by the intraseasonal oscillation of the tropical easterly jet. This anticyclone system must be affected by the interannual variation of that jet too. The disclosure of the cause of this interannual variation definitely would facilitate our understanding of the interannual variation of weather systems on both the upstream and downstream sides of that jet, in addition to that over the Indian monsoon region.

Only interannual variations of planetary-scale divergent circulations, stationary eddies, and the tropical easterly jet from the past decade were analyzed and examined in this study. Actually, according to Chen and van Loon (1987) and the present study, interannual changes in strength and position of the tropical easterly jet took place a number of times in the past three decades. As revealed from the present study, the planetary-scale divergent circulation is crucial to the maintenance and interannual variation of the tropical easterly jet. However, divergent winds were not well contained in the analyzed observational data before the GDAS data of operational centers became available. Thus, the conclusion concerning the relation between interannual variations of the tropical easterly jet and those of planetary-scale divergent circulation should be considered as tentative. It is therefore highly desirable that this pilot study be reperformed with the multi-decade GDAS data. It was reported recently by Kalnay and Jenne (1991) that the National Meteorological Center (NMC) is undertaking a task of reassimilating the global data over the past several decades with the NMC GDAS. It is our hope that a definite conclusion of this study can be reached with this multi-decade NMC GDAS data.

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